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CONCLUDING REPORT ON GRANT NO. NGR 07-010-002
ON COOPERATIVE RESEARCH EFFORT

between

Dr. Donald F. Heath
Planetary Radiations Branch
Laboratory for Atmospheric
and Biological Sciences

Goddard Space Flight Center

and

The Department of Physics
Fairfield University
Fairfield, Connecticut

"Measurement of Hydroxyl Temperatures in the
Upper Atmosphere with a High Sensitivity Spectrometer"

submitted

by

Dr. James H. McElaney

and

Dr. Abbas Khadjavi

The Department of Physics
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Fairfield, Connecticut



Background of NASA Grant #NGR-07-010-002

Dr. Donald F. Heath of the Goddard Space Flight Center suggested some avenues of cooperative research to be conducted by himself and Dr. James H. McElaney of Fairfield University and later by Dr. Abbas Khadjavi of Fairfield University. This cooperative research would involve experiments of mutual interest. Dr. Heath was involved not only in a study of the ultraviolet region of the optical spectrum, but his investigations in this area brought him into areas which bear on the acquisition and evaluation of experimental data related to atmospheric studies. His work included experiments flown on sounding rockets, a study of the effects of radiation on optical materials, and an increasing interest in auroral studies. Dr. Heath has published articles on these and other subjects.

Dr. James H. McElaney of Fairfield University worked with Dr. Heath for three summers at the Goddard Space Flight Center. During the summers of 1966 and 1967, he was employed as a consultant at the Goddard Space Flight Center Summer Workshop. He received a NASA-ASEE Fellowship for the summer of 1968. He worked with Dr. Heath in the study of the effects of electron irradiation on spectrally selective photocathodes for the ultraviolet and the study of the effects of proton irradiation on optical materials. He also worked on equipment for the measurement of the absorption cross sections of gases in the vacuum ultraviolet region. Dr. McElaney did previous work in the field of free-ion spectroscopy at the Johns Hopkins University.

Part I

Several experiments were proposed initially. The first experiments involved ground based measurements in conjunction with rocket borne instruments to be launched at Churchill, Canada.

Three rockets were to be launched from the Churchill Rocket Range. Two of these rockets were to be fired almost simultaneously. The first rocket to be fired, the Nike-Apache, contained an experiment for measuring the neutral gas temperature. The payload of this rocket contained a photometer package to measure the intensity and volume emission of molecular nitrogen, the nitrogen molecular ion, and atomic oxygen. Ground based measurements were to be made at the same time to determine if the temperature of the nitrogen molecular ion was the same as the neutral gas temperature.

Approximately one minute after the launch of the first rocket, a Nike-Tomahawk was to be launched bearing a spectrometer for measuring the atmospheric flux of incoming electrons, and carried a concave grating spectrometer for measuring the aurora in the 500-1100 A region. The rocket carried a thin film photometer to determine the auroral emission in the 200-1100 A region. Flights were scheduled that the Nike-Tomahawk would overtake the Nike-Apache and thereafter the Nike-Tomahawk would measure the electron flux which produces the optical emission seen by the Nike-Apache payload.

Part II

In recent years, there has been an interest in measurements of the rotational temperature of aurorae as well as height dimensions of auroral forms. Vegard undertook measurements of rotational temperatures in 1947 and 1941. For his dimension he used the unresolved negative-group bands of N_2^+ at 3914 Å and 4278 Å. The average temperatures obtained by him, about 230 K, are reasonable for kinetic temperatures at 100 km. However, the same temperature was obtained from aurora at greater heights. This did not seem to agree with the current idea that the kinetic temperature is believed to increase rather rapidly above a height of about 100 km. Hunten (1961) seemed to show strong evidence that the rotational temperature measured from the rotational distribution in the first negative bands of N_2^+ is equal to the kinetic temperature of the atmosphere.

In many previous temperature measurements, the rotational structure of the N_2^+ bands could only be resolved by photographic methods (Vallance Jones and Harrison, 1955; Montalbetti, 1957). These spectra, therefore, do not represent the temperature of an individual auroral form, but rather an average over a period of time. The energy limitation of most of the photographic and photoelectric spectrometers up to the present time were so limited that it was not possible to resolve the rotational structure as well as would be desired. The temperatures then had to be determined from the profile of the P + R branches. Work by Suter and Heath (1970) indicated that the Ebert-Fastie spectrometer with 15 cm slits and a 1-meter focal length can effectively resolve the N_2^+ rotational structure. The instrument was used to measure the lower borders of auroral forms.

Part III

As part of this cooperative research effort, measurements of the hydroxyl temperatures in the upper atmosphere have been made with a high sensitivity spectrometer. For five weeks in January and February of 1975 and 1976, measurements of these temperatures were made to determine the variation of the rotational temperatures of OH with stratospheric warming events occurring over the New England area. In addition, the OH temperatures were recorded during the summer of 1975 in the area of Fairfield, Connecticut. As a result of this effort, data has shown a wide fluctuation in the OH temperatures in the upper atmosphere amounting to as much as a couple of hundred degrees in the course of an evening. It was not yet possible to relate the variations in the OH temperature measurements with the stratospheric warming events because of the inclement weather conditions which occurred during January 1975, 1976. The research direction, however, seemed valuable and the equipment used for the temperature measurement yielded outstanding results. Therefore further attempts were made to measure hydroxyl temperatures in the New England area. Heath (1970) indicated that the Ebert-Fastie spectrometer with 15 cm slits and a 1-meter focal length can effectively resolve the N_2^+ rotational structure. The instrument was used to measure the lower borders of auroral forms, and field work with the instrument indicated that it would produce highly satisfactory results.

The rotational-vibrational bands of OH were discovered in the nightglow by Meinel [1] these emissions have been the object of a great deal of study by many observers. Inasmuch as the lines of the P-branches of these bands may be well separated using a good spectrometer, the rotational temperatures may be obtained from the intensity distribution of these lines. Since the temperature of the emitting atmosphere and the rotational temperature determined from the OH bands seem to be equivalent, many investigators have studied the variations which are present in the intensity and temperatures of OH. [2,3]

The heights of the hydroxyl emissions have been measured many times using either the VanRhijn method or by rocket measurements. While there is some discrepancy in their results, the altitude of the maximum intensity of the emission lines may be considered to be about 90-95 km. [4,5,6] While additional rocket measurements of altitude could be profitably carried out to determine variations in the levels of hydroxyl emission and to see how it varies with the time of day, we can reasonably assume for our purposes that the source of emission is at this altitude.

In addition, studies have been systematically conducted to discover any variations with season or latitude in the intensity and the rotational temperatures of OH. Some authors have found a maxima in winter and minima in summer. Some studies seem to indicate a variation of the OH rotational temperature with latitude. [7,8] The difference in seasons as found by Wallace [9] in lower latitudes may indicate a relatively consistent height level of the OH layer throughout the year at these latitudes. The results of the tempera-

ture determinations show a large variation in the range between 180 and 300 °K. Some of this variation may be due to experimental difficulties.

Russian investigators, such as N. N. Shefov [10] and V. I. Krassovsky, [11] have found a range of sporadic variations of temperature which exceed the amplitudes of the more regular components. Rapid variations in intensity of the rotational temperatures have been obtained by them. The data they have obtained indicates a wavy phenomena or movements of inhomogeneities at a speed of some 100 meters per second. These rapid changes in rotational temperature may not be due to the real change in temperature, since this would require rapid changes in the inflow and outflow of heat. The fluctuations may be due to changes in the height of the emitting lines and the changes in space and in time which have been noted may indicate not only turbulent movements in the upper atmosphere, but also to oscillatory motions in it.

We would like to examine these periodic variations, calculate the temperature changes which are taking place, and if possible relate these results to the presence of gravity waves. The OH temperatures would be monitored continually throughout the night. The 1-meter Ebert-Fastie spectrometer is a very high resolution instrument capable of resolving the Meinel bands easily and detecting very weak signals. It is also capable of scanning a wavelength region in approximately 10 seconds. These results may then be recorded in real time or the signal may be averaged over an indefinite time period.

Instrumentation

The spectrometer which is to be used to determine the temperature variations of OH will be a modified Ebert-Fastie spectrometer which

has a focal length of 1 meter. The spectrometer is mounted in a strong fork mount so that it may be changed in altitude and azimuth. A fine adjustment in its orientation may be made with a motor drive. It will be equipped with a plane grating which has 1200 grooves per millimeter and an effective area of approximately 15.4 x 20.6 centimeters. The grating is blazed at 57°, which is particularly suited for our region of interest, mainly 8300-8600Å and 8800-9100Å. The entrance and exit slits of the spectrometer are circular and are 15 cm long. The slit opening may be adjusted in a series of steps from 0.1 mm to 10 mm.

The grating is operated in the saw-tooth mode by a rotating cam. The extent of the wavelength interval which is scanned depends on the rise of the cam. The wavelength region can be adjusted by a micrometer device. The field of view of the spectrometer may be varied by means of a telescope of 95 cm focal length from 10 degrees to a fraction of degree. The telescope is located in front of the entrance slit and is movable. The detector to be used is a RCA tube having a gallium-indium-arsenide photocathode, with the spectral sensitivity most suited for our region of interest.

A thermoelectric cooler is used to reduce the dark current to a suitable level. The output of the photometer is measured with a pulse counting system.

Determination of Rotational Temperatures from the Meinel Bands of Atmospheric Hydroxyl Molecules

The vibration-rotation bands of atmospheric OH in the near infrared were used to monitor the temperature of the molecules. These bands occur in the visible and the infrared ranges of the

spectrum. [12] The constraints of our particular spectrometer system, however, limited the observable bands roughly to the range of 7000-9000 Å. This range could only be covered in the first order at a grating angle of 26°-35°, far from the geometrical blaze angle. (Part of the range could also be covered in the second order at near grazing incidence.) Experimental curves giving the efficiency vs. angle of incidence for the grating, however, indicated that, due to a fortuitous polarization dependent anomaly in the grating efficiency, this range of angles actually was highly favorable.

We then searched this wavelength range. The vibrational bands occurring in this range are 8-3, 4-0, 9-4, 5-1, 6-2, and 7-3. The strongest signal was obtained from the 6-2 band (band head at 8280 Å).

[13] Subsequently, this band was used in obtaining temperature data. One of the first spectra we recorded is shown in Figure 1. Usually the real-time data signal-to-noise ratios were rather poor and to obtain reasonable temperature measurements 2^4 or 2^5 10 second scans were averaged. In Figure 2 a typical average spectrum is given together with a sample of the real-time signal. In this figure the P_1 lines (of the $^2\pi_{1/2}$ state) are labeled with their rotational quantum number J'' . The P_2 lines (of the $^2\pi_{1/2}$ state) are partially resolved and give the characteristic intensity alternation of the band. The molecular constants of OH, according to Hersberg, [14] are listed in Table 1. To obtain the rotational temperatures a value of $B_6 = 14.352$ was used. In Figure 3 the line intensities of the data of Figure 2 are plotted against the rotational energy. It is evident that the intensities do indeed follow a Boltzmann distribution very closely. Fitting a straight line to this data the temperature is obtained from the slope of the line and is $T = 605 \pm 30^\circ\text{K}$. In this

temperature determination equal weight has been assigned to the five line intensities ($P_1(2)$ through $P_2(6)$) considered.

Taking the average of 2^5 scans of 10 each, a temperature measurement requires approximately 5 minutes and temperature drifts can be followed accurately. The averages recorded are weighed with an exponential function of time, the last scan having a maximum weight. As each scan is added to the average, the weight assigned to the previous scans are reduced by a constant factor. This was done for convenience in recording, and to avoid losing data acquisition time while recording an average. We found no measurable difference between the temperatures obtained from a weighted average and an unweighted one. A block diagram of the spectrometer and the associated electronics is given in Figure 4. The spectrometer is a 1 m Ebert described elsewhere. An RCA Quantacon photomultiplier tube is used in this work. These photomultipliers have very small photocathodes. In our present system most of the signal is lost in coupling the spectrometer exit slit of 6° height to the photocathode ($1/4" \times 3/16"$) by means of an optical pyramid. We plan to improve this coupling in our future work and a gain in signal of at least an order of magnitude is expected with improved coupling.

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Fig. 1 The 6-2 band of Meinel OH spectrum. This curve is the average of 16 scans. (7/11/1974)

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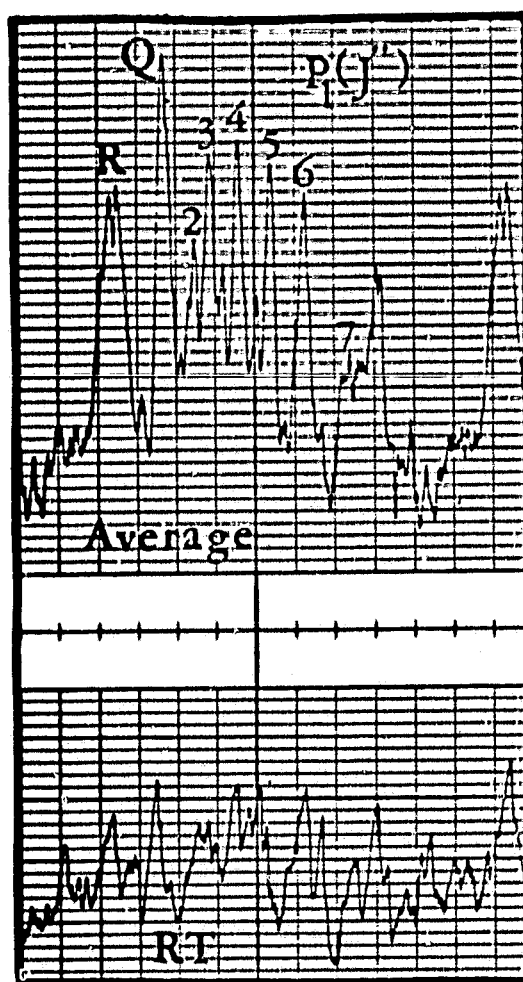


Fig. 2 Real-time and average spectra for the 6-2 band of OH. The $P_1(J'')$ lines are labeled with J'' . (1/28/76)

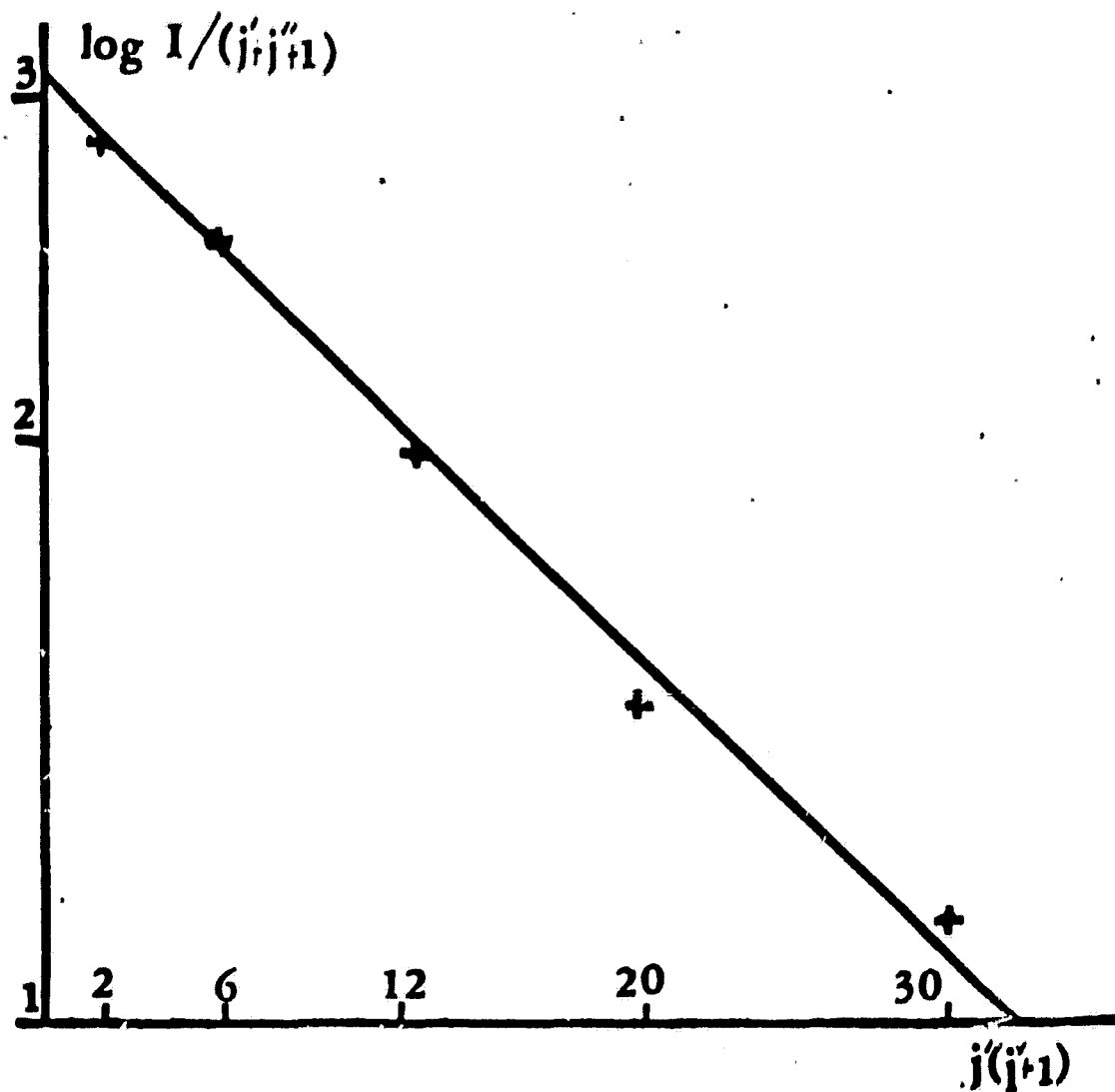


Fig. 3 Log plot of intensity vs. energy for the data of Fig. 2.

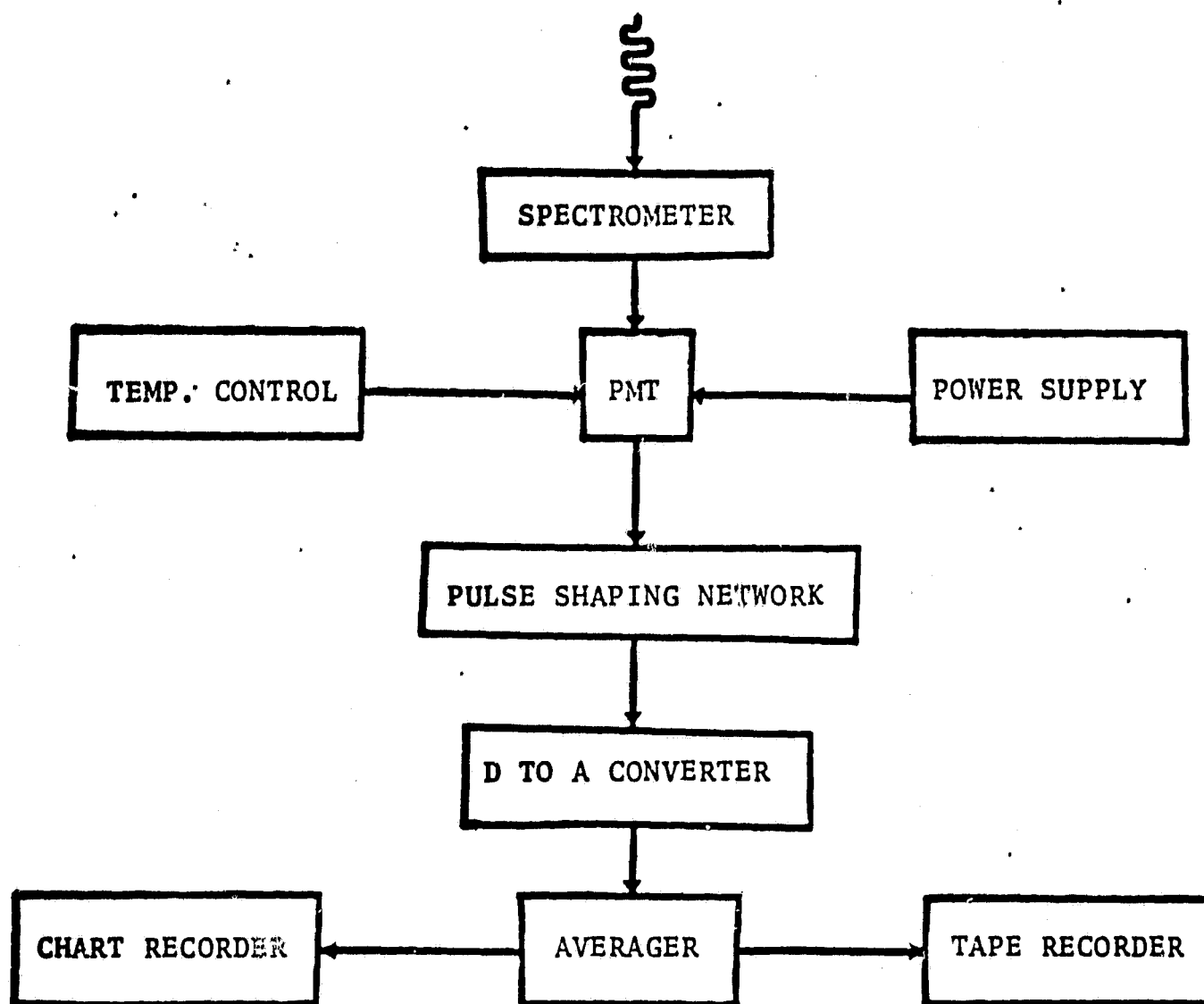


Fig. 4 Block diagram of the spectrometer and the associated electronics.

TABLE I

Rotational and vibrational constants in the ground state of OII radical. (Ref. 3)

B_e	=	18.867	cm^{-1}
α_e	=	0.708	"
γ_e	=	0.00207	"
ω_e	=	3739.94	"
$\omega_e x_e$	=	86.350	"
$\omega_e y_e$	=	0.9046	"
$\omega_e z_e$	=	0.05763	"
r	=	0.97078	\AA

γ_e is the coefficient of $(v + \frac{1}{2})^2$ in the expansion of B_v .

FIGURE CAPTIONS

Fig. 5. Real-time and average spectra for OH 6-2 band.

$P_1(2)$ through $P_1(6)$ lines are shown.

Fig. 6. Plot of $\log I/(J' + J'' + 1)$ vs. energy for data of Fig. 5.

Fig. 7. Rotational temperature of OH vs. time for the evening of 5/2/78.

Fig. 8. Rotational temperature of OH vs. time for the evening of 5/3/78.

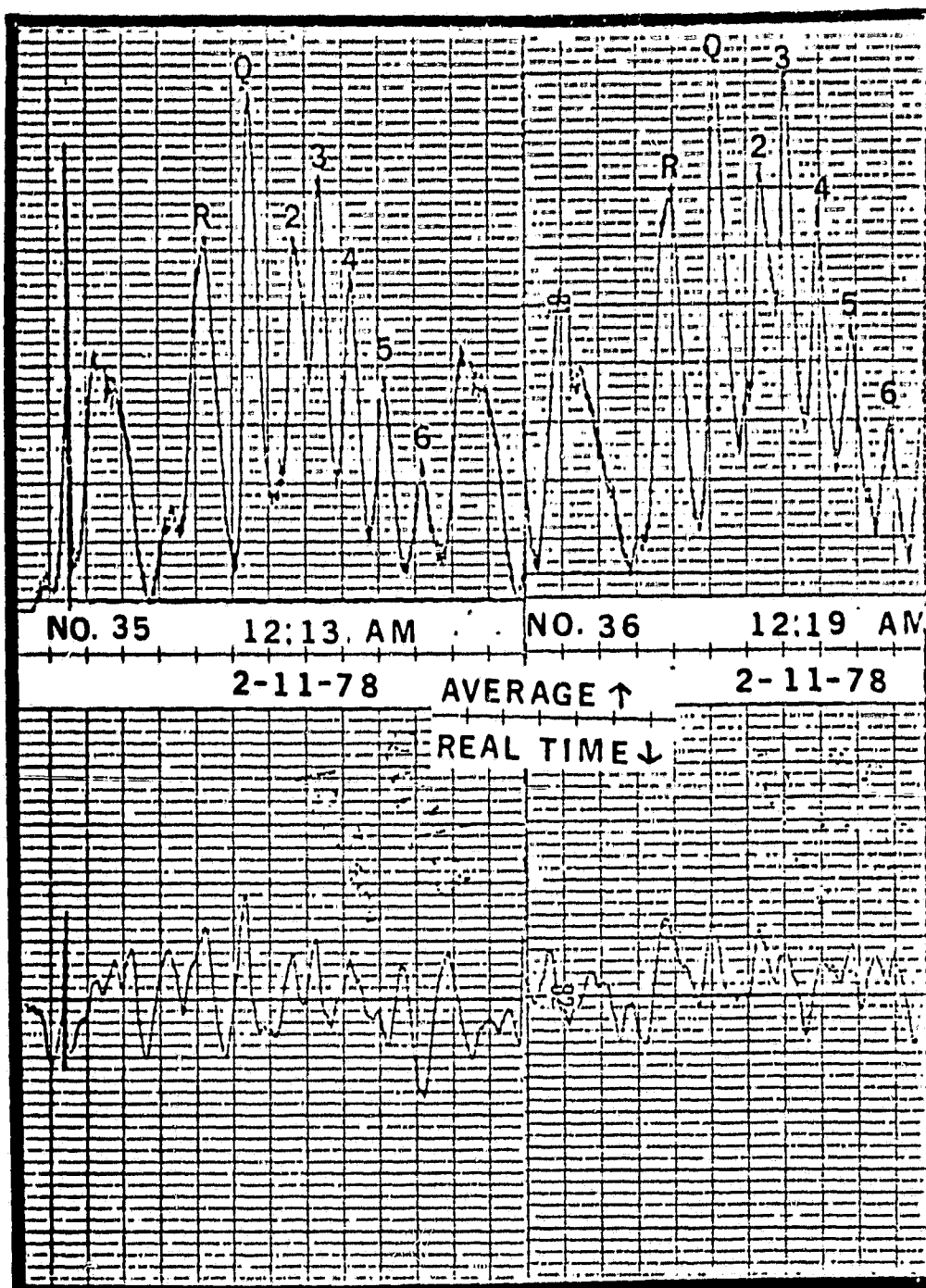


Fig. 5

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S 306 363 275 193 113

X P Y

1/11/78 12:13 AM CURVE 35

1.88

DATA FOR GRAPH OF LOG I/J VS. J(J+1)

WITH BEST FIT LINE $Y=A+BX$ SLOPE: $B = 0.0325774 \pm 1.03317 \%$

1.66

-INTERCEPT: $A = 1.90225 \pm 0.282809 \%$ -INTERCEPT: $A/B = 58.3917$ OPERATIONAL TEMPERATURE: $T = 275 \pm 3 \text{ } ^\circ\text{K}$

1.44

1.22

0.99

0.20 0.76 1.32 1.88 2.44 3.00

 $X \times 10^{-01}$ $Y \times 10^{-00}$

S 330 400 309 209 128

X P Y

1/11/78 12:19 AM CURVE 36

1.92

DATA FOR GRAPH OF LOG I/J VS. J(J+1)

WITH BEST FIT LINE $Y=A+BX$ SLOPE: $B = 0.0326725 \pm 0.989721 \%$

1.69

-INTERCEPT: $A = 1.99167 \pm 0.259508 \%$ -INTERCEPT: $A/B = 60.9587$ OPERATIONAL TEMPERATURE: $T = 275 \pm 3 \text{ } ^\circ\text{K}$

1.47

1.25

1.03

0.20 0.76 1.32 1.88 2.44 3.00

 $X \times 10^{-01}$ $Y \times 10^{-00}$

Fig. 6

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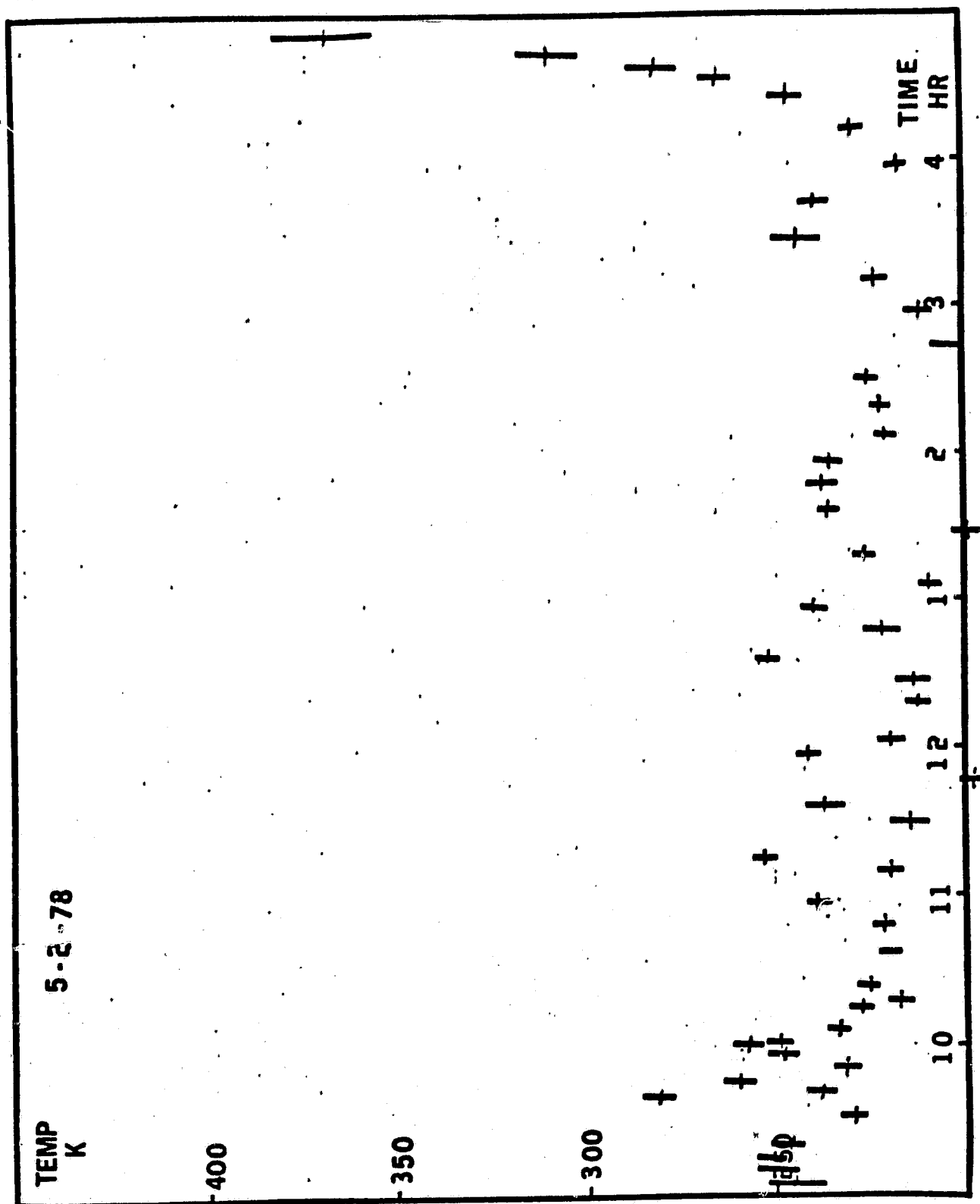
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Fig. 7

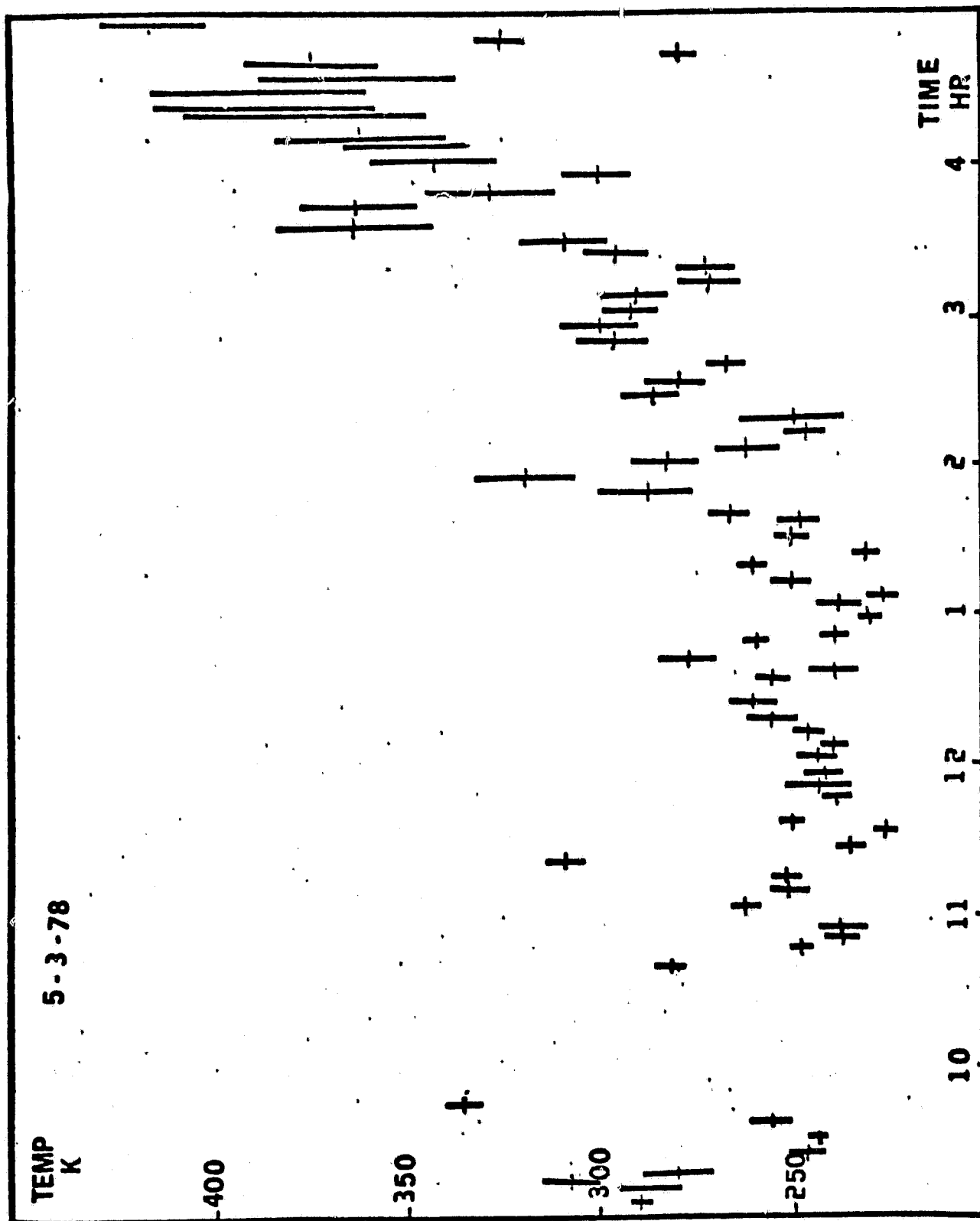


Fig. 8

Travel Associated with Research and Grants

April 1968 Fort Churchill, Hudson Bay, Canada

Trip to evaluate the possibility of measuring auroral heights in the region of maxima occurrence of aurora and evaluate the rocket launch facilities at the Canadian National Research Center

October 1969 Fort Churchill, Hudson Bay, Canada

Measurement of auroral temperatures and altitudes during the time of rocket launches from the launch facilities at Fort Churchill

January 1970 Fort Churchill, Hudson Bay, Canada

Measurement of energy deposition by rocket launch as well as temperature and altitude measurements

September 1970 Fairbanks, Alaska

To evaluate rocket launch facilities and the auroral observatory facilities at the Geophysical Institute of Alaska in preparation for auroral studies

March 1971 Fairbanks, Alaska

To measure the temperatures and heights of stable auroral arcs.

February 1972 Fairbanks, Alaska

To measure the temperatures and heights of stable auroral arcs

March 1972 Fairbanks, Alaska

Trip to measure variations in temperatures and altitudes of stable auroral arcs.

December 1974 Acton, Maine

Trip of four weeks' duration for measurement of OH temperatures in the upper atmosphere

December 1975 Warren, Vermont

Five week trip for measurement of OH temperatures in the upper mesosphere

August 1977 - January 1978

During these dates the equipment was on loan to the University of Michigan. It was used at a site in Africa for radiation measurements.

Data and Results

In each of the three projects undertaken, the overall results varied. The trips taken to Fort Churchill, Canada, were for the purpose previously indicated, namely to provide ground based measurements of the auroral temperatures at the time of the rocket launch and to compare these measurements with the results obtained from rocket measurements, and with altitude measurements of the auroral forms provided by the rocket range personnel. However, the booster rocket exploded shortly after launch and the rocket payload was lost as a result of the mishap. At the same time, the observatory ceased altitude measurements. Consequently the primary objectives of the total experiment were certainly not realized. The high-sensitivity spectrometer performed excellently as expected, however. Temperatures were recorded for the auroral forms during the display. This data has been reduced, but it is not possible to correlate these temperatures with altitude measurements or rocket data.

The goals desired from the trips to Alaska varied over a period of time. Initially an examination was made of the rocket launch facilities under construction by the Geophysical Institute of the University of Alaska, with the intent of using these facilities for a rocket launch instead of those at the Canadian Research facility at Fort Churchill, Canada, which was being phased out. Shortly thereafter the sounding rocket program at the Goddard Space Flight Center was also curtailed. Thus it was decided to attempt measuring the temperatures and altitudes of the borders of stable auroral arcs using the observatory of the Geophysical Institute at Fairbanks, Alaska. For a period totalling several weeks, observations were

made and temperatures determined for auroral forms which were observed. Again the instruments provided accurate temperature measurements, but the auroral forms within the field of view of the instrument were not the stable auroral arcs which had been hoped for. It was decided that further expenditures for altitude measurements of the auroral forms observed were not warranted.

Measurements were made of temperatures in the lower mesosphere from sites in Vermont, Connecticut and Maine during January to obtain temperature variations which might occur during periods of stratospheric warming. No warming events occurred during these years, at least in those regions where our experiment was being conducted. The data collected, however, will be incorporated into the survey of temperature variations in the upper atmosphere, a project to which the spectrometer was immediately turned. Some thousands of these measurements have been made and temperatures calculated. The data reduction process has been computerized and each measurement displayed as shown in the accompanying pictures. All data obtained is being sent to Dr. Donald Heath, the NASA director of these experiments.

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Dr. James H. McElaney

Vita

Dr. McElaney was born in [REDACTED]. He attended schools in that city and was graduated from Boston Latin School. At Boston College he received an A.B. and M.A. in Philosophy. He also received a Ph.L. from Weston College, and some time later the S.T.L. degree from the same college.

He entered the Physics Department at Johns Hopkins University in Baltimore, Md. where in 1964 he received his Ph.D. His area of specialization was in the field of free-ion spectroscopy. His dissertation was written under the direction of the late Dr. Gerhard H. Dieke.

He has taught as an instructor in physics and in mathematics at Boston College and at Holy Cross College. In 1963 he joined the Department of Physics at Fairfield University, where he is presently Professor of Physics and Astronomy. Dr. McElaney served as Chairman of the Physics Department for twelve years.

He is a member of the American Physical Society, American Association of University Professors, American Association of Physics Teachers, and the Optical Society of America.

Dr. Abbas Khadjavi

Vita

Dr. Abbas Khadjavi was [REDACTED] where he attended elementary and secondary schools. He attended the University of Wisconsin from September, 1957 to June, 1961, receiving a Bachelor of Arts degree in Mathematics. From September, 1961 to January, 1967, Dr. Khadjavi attended Columbia University, New York, New York, receiving his Master of Arts and Ph.D. in Physics. While at Columbia University he participated in research in atomic physics and was a teaching assistant. His further experience includes 2 1/2 years of research in atomic physics at the IBM Watson Laboratory, New York, New York, and 2 1/2 years as a Senior Scientist at the Westinghouse Research Laboratories located in Pittsburgh, Pa. His research at Westinghouse was in plasma physics. In September of 1969 he joined the Department of Chemistry at Columbia University for a one year post-doctoral appointment for research in molecular physics and gas lasers.

Dr. Khadjavi was appointed Assistant Professor in the Physics Department at Fairfield University in September, 1970. He has taught courses in Electronics and Optics in addition to laboratory courses in both these subjects. Dr. Khadjavi is presently an Associate Professor of Physics.

NASA EQUIPMENT ON LOAN

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2.	Carrying Case		EA	1
3.	HP Signal Analyzer Mod.:5480A Ser.#832-00109	210378	EA	1
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11.	Spectrometer Accessories: Telescope Housing Photo Tube housing, Optical Pyramid, Mirrors Lenses, Filters, associated cables, wavelength cams			
12.	PFR Power Supply	243548	EA	1

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